Uncertainty Quantification and Validation of Equipment Response to Underwater Shock Loading

Ken Hu, Dave Manko, and John Red-Horse
Sandia National Laboratories

Thomas Paez – Thomas Paez Consulting

National Defense Industrial Association: Physics-Based Modeling
November 7, 2012

Outline

- Overview of Full Ship Shock Trial Alternative program
- Verification and Validation at Sandia
- Validation approach for the FSST Alternative
- Comments/ Path forward

Full Ship Shock Trials (FSST)

- Manned ships subjected to controlled, Underwater Explosions (UNDEX) while at sea
- Requirement for qualification of a class of ship

Sandia National Laboratories

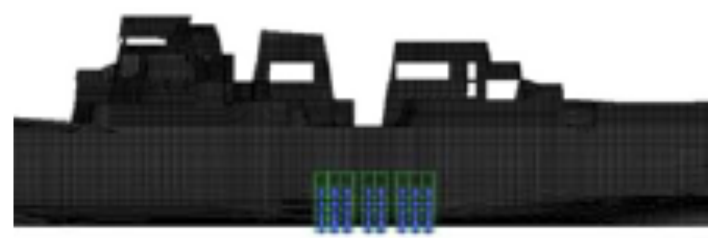
FSST Alternative Program

- Integrated Product Team formed to develop an FSST Alternative using Airguns instead of UNDEX
- Modeling & Simulation working group lead by NSWC Carderock Survivability and Weapons Effect Division
  - Dr. Thomas Moyer
  - Chris Van Valkenburgh
- "To evaluate the ability of airguns to induce failures and cause damage to shipboard equipment items and systems in a manner similar to UNDEX at <u>Shock Trial levels</u>"

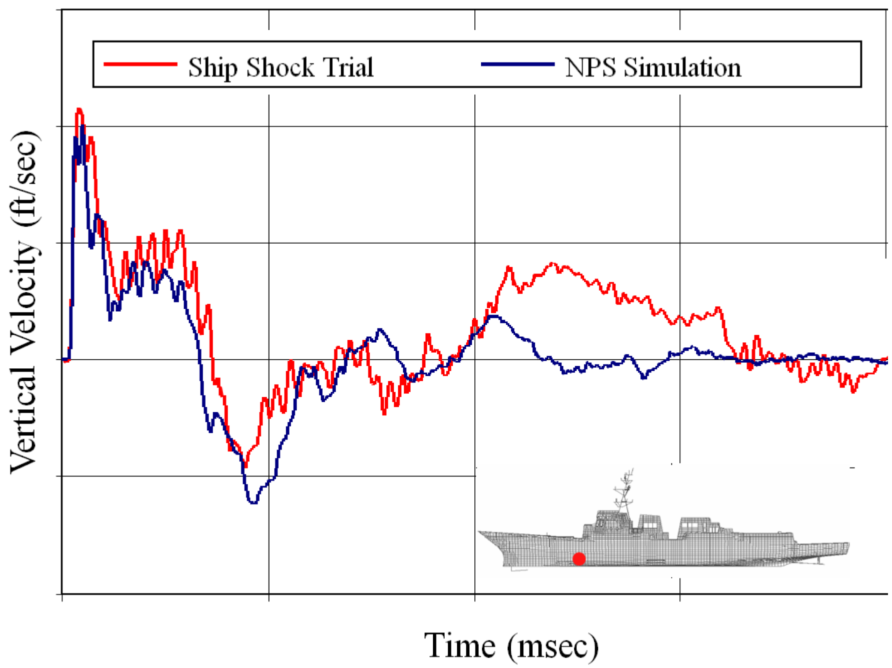
FSST Alternative

- May be feasible to replace FSST with more controlled, smaller scale testing w/ Airguns
- Advantages:
  - Lower Cost
  - Less environmental impact
- Must still assess survivability
- Determine feasibility using Modeling & Simulation
- **Must establish credibility of M&S predictions**

Airgun Loading Simulation



M&S Alone is Not Enough



http://www.nps.edu/research/Documents/SVCL_web_sanitized.ppt

- Compare ship response
  - Test vs. simulation
- Visual comparisons ≠ validation
- Are differences important?
- How to deal with
  - Variability
  - Uncertainty
  - Errors

Definitions

- Verification – "Are we solving the equations correctly?"
  - Correctness of implemented mathematical algorithms.
- Validation – "Are we solving the right equations?"
  - Correctness of physical models and sufficiency for the application.
- Uncertainty Quantification (UQ):
  - Statistical propagation of uncertainty through a simulation model, and statistical interpretation of model response.

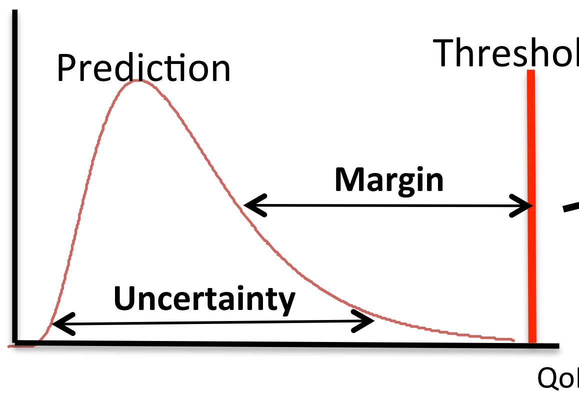
Sandia Perspective on Verification, Validation, and Uncertainty Quantification

Sandia National Laboratories

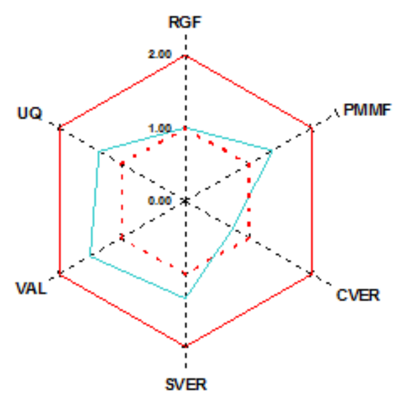
Risk Informed Decision Making

Testing of high consequence system

Testing + Simulations
→ Quantified Margins and Uncertainties (QMU)



Credibility That is Assessed and Communicated
→PCMM



Decision Makers

Sandia National Laboratories

M&S Supporting High Consequence Decisions

- Underground testing used to test weapon effects
- M&S replaced underground testing

- Must establish credibility in all aspects of prediction
  – Model Development
  – Uncertainty Quantification (UQ)
  – Verification and Validation (V&V)
- Must effectively communicate the credibility
  – Predictive Capability Maturity Model (PCMM)

Sandia National Laboratories

What Gives M&S Results Credibility?

Seven categories of PCMM

- RGF: Representation and geometric fidelity
- PMMF: Physics and material model fidelity

M&S

- CVER: Code verification
- SVER: Solution verification
- VAL: Validation

Validation

- UQ: Uncertainty quantification

UQ

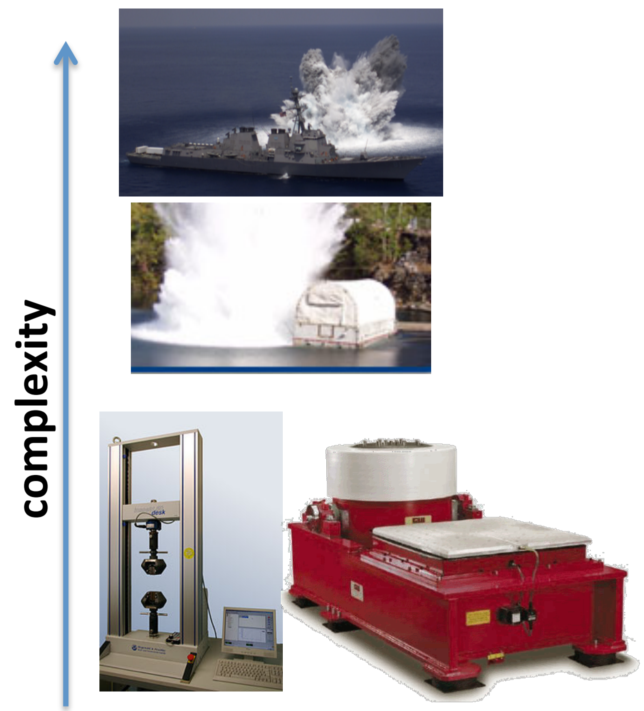
- Documentation and archiving

Key idea: Gather wide range of evidence on all categories

Sandia National Laboratories

V&V Hierarchy

- Cannot run every test and all simulations
- Gather V&V evidence at many levels of complexity
- Build confidence in M&S capability at all levels
  - Calibrate models to test data
  - Validate predictions



→ **Predictions + uncertainty and credibility estimates**

Images from hitest.com, abtronix.com, wikipedia.com

FSSTA Validation Process

FSST Alternative – Goals

- End goal: Validate models in order to compare effects of UNDEX and airguns on a full ship
- Full ship models very complex, data is limited
- FY12 Goal: Demonstrate procedures for validation of models *for the purpose of* comparison of UNDEX vs. airgun effects
  - Use simpler test cases
  - Floating Shock Platform (FSP)
  - Deck Simulator Fixture (DSF) attached to FSP

Validation Checklist

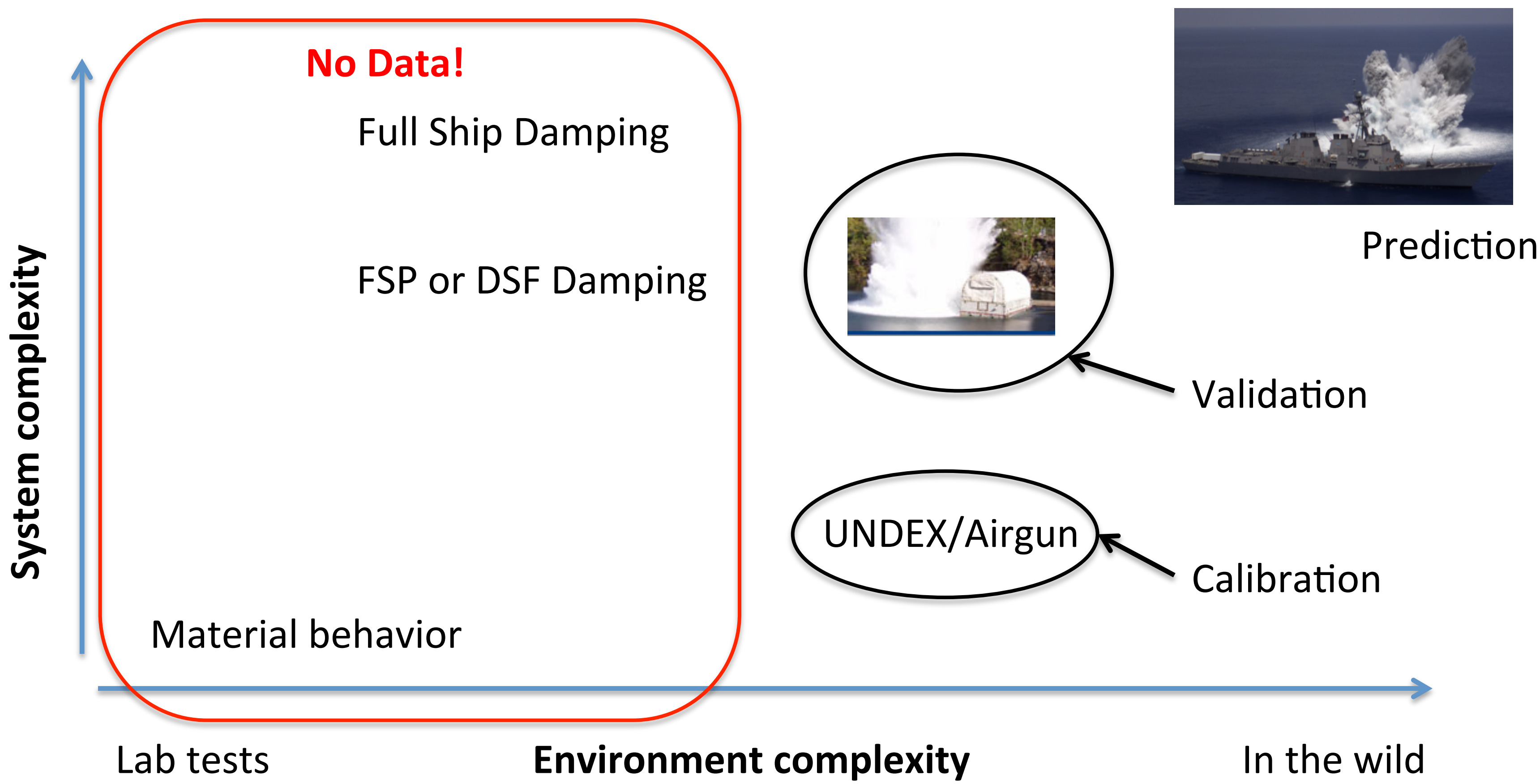
- Use hierarchy to make best use of data
- Define Quantities of Interest, derived from responses
- Identify and characterize sources of uncertainty
  - Both physical sources and modeling sources
- Propagate effect of uncertainty to simulation responses (UQ)
- Compare Quantities of Interest from test and simulation (Validation)

Tests

- UNDEX loading on FSP, FSP+DSF
  - Validate combined UNDEX, FSP, DSF models
- Underwater Airgun shots
  - Calibrate Airgun model (Weidlinger Associates)
- Airgun loading on FSP, FSP+DSF
  - Validate combined Airgun, FSP, DSF models

- No data for UNDEX shots – models already exist
- No data on FSP, FSP+DSF with simpler loading

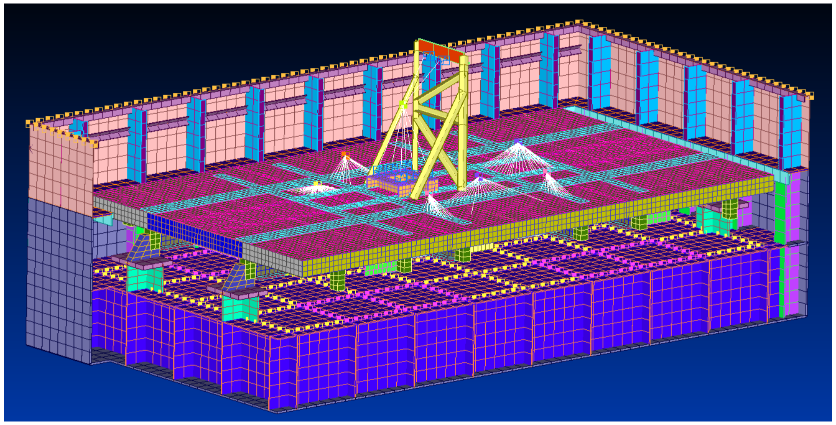
Validation Approach for FSST Alternative



- Strategy limited by available data

Codes & Models

- Gemini
  - Hydrocode
  - NSWC Indian Head

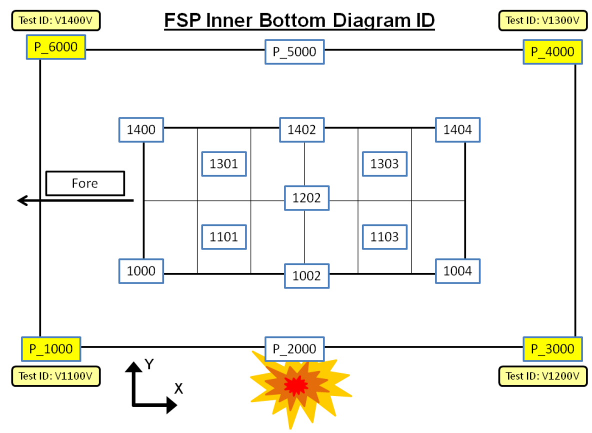


- SIERRA Mechanics – Salinas
  - Structural Dynamics
  - Sandia National Labs

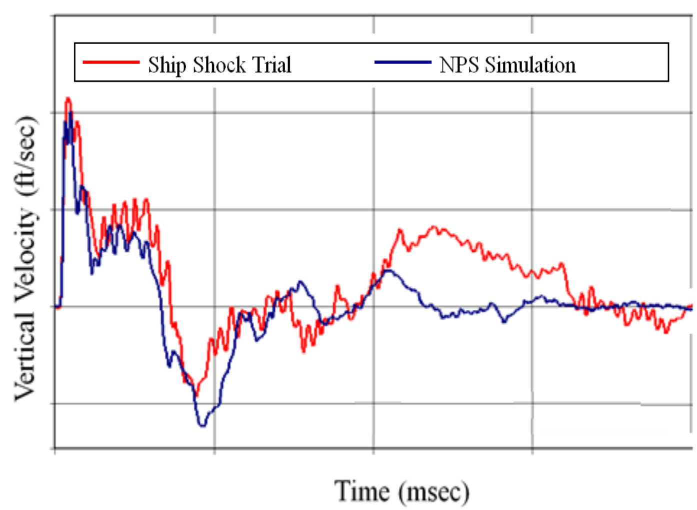
Integrated into Navy Enhanced Sierra Mechanics (NESM)

Test Data / Model Responses

- Tests
  - Gages (velocity / acceleration)
  - Several locations



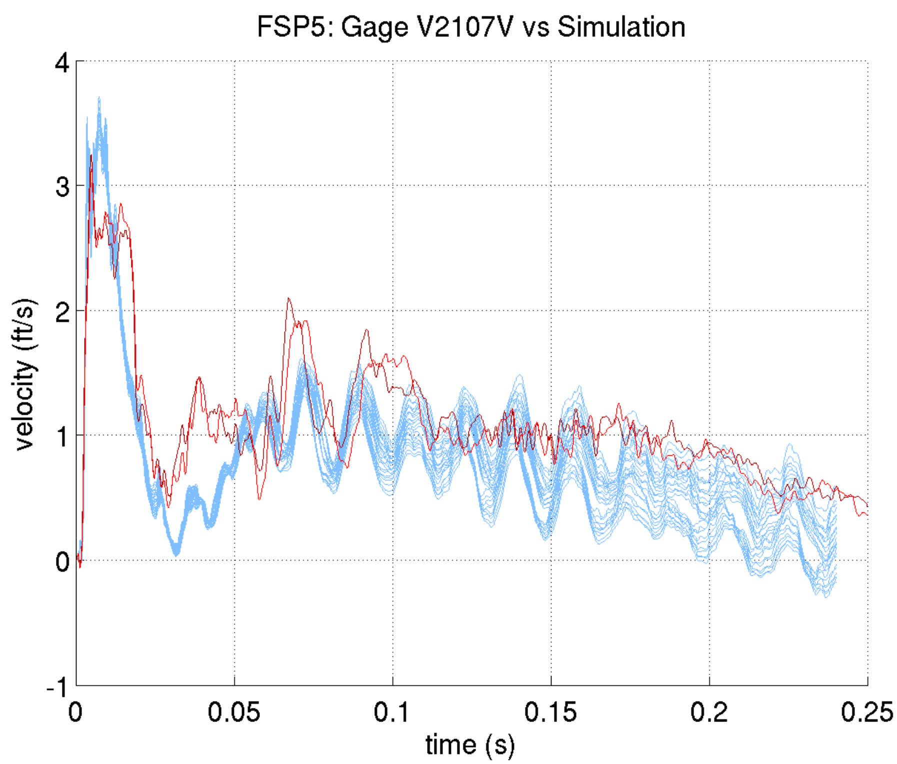
- M&S
  - Displacement, velocity, acceleration response
  - Match location of gages



http://www.nps.edu/research/Documents/SVCL_web_sanitized.ppt

Sandia National Laboratories

Quantities of Interest



- Response time history
- What features are important?
- Reduce information content to a few scalar values
- End goal – prediction of damage potential

Proposed QoI's

- Windowed acceleration(1)
- Windowed pseudo-velocity(1)
- Windowed RMS(2)
- Temporal moments – first five moments
- Windowed input energy(1)
- Windowed strain energy(1)
- Windowed energy equivalent velocity(1)

(1) Five gaussian windows centered at 10, 20, 40, 80 and 160 Hz with 10, 20, 40, 80 and 160 Hz widths

(2) Ten windows evenly spaced from 0 – 250 ms with minimal overlap

Sandia National Laboratories

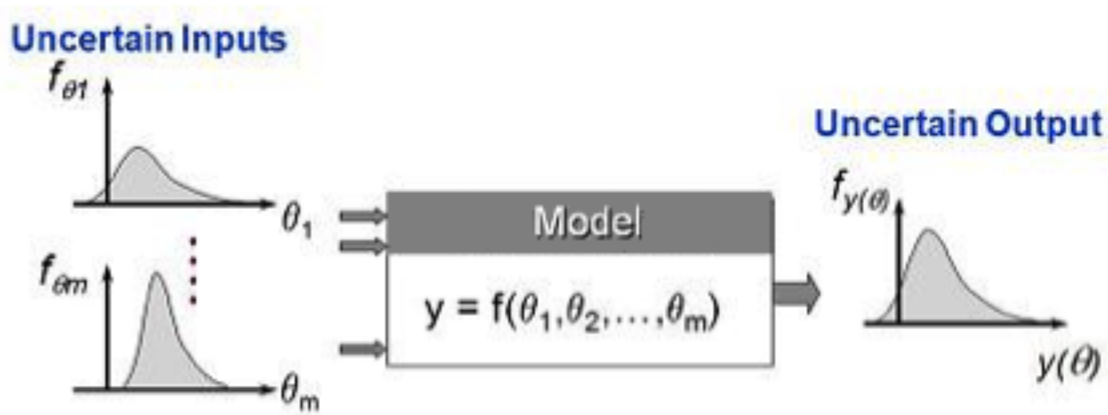
Significance of QoIs

- Used to assess some feature of the response
- Windows allow certain time or frequency ranges to be analyzed independently
- Subset of QoIs may correlate with damage potential
  - Strain energy windowed near a fundamental frequency
- May not be necessary to match velocity time history

- Match QoIs → simulation is useful

UQ Concept

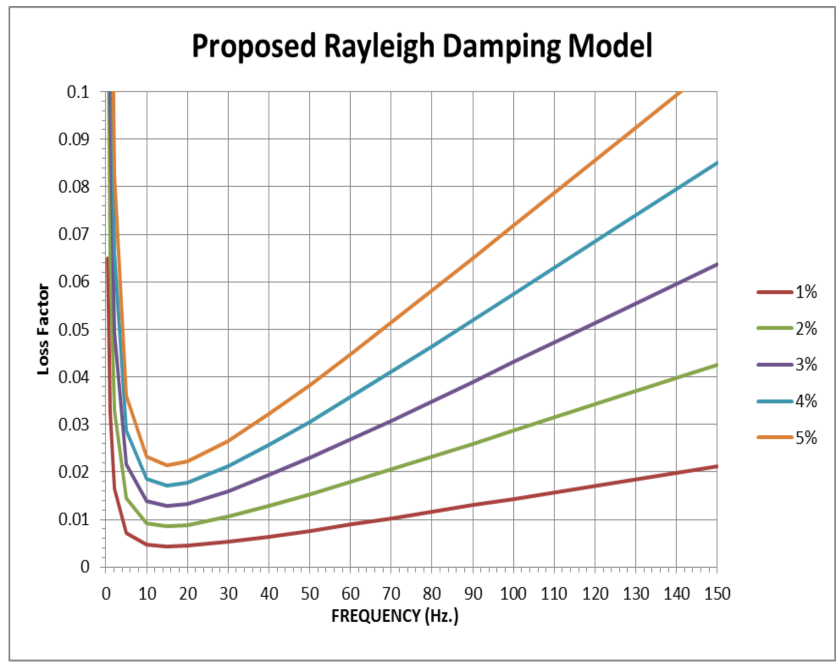
- Represent uncertainty in model inputs with probability distributions
- Resulting output from the model is also uncertain



- UQ methods – estimate the output distribution

Input Uncertainty

- Two sources of uncertainty in M&S
- Effective charge mass $\pm 5\%$
  - Assumed a uniform distribution, centered at nominal mass
- Damping Factor
  - Controlled two parameters in a Rayleigh Damping scheme
  - Bounds were 1 and 5%
  - Assumed uniform distribution



Sandia National Laboratories

UQ w/ Polynomial Chaos Expansions

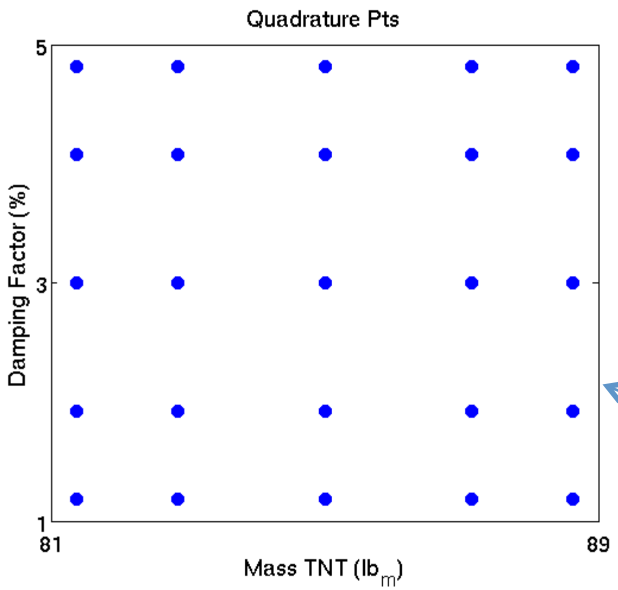
- Uniform Basis Random Variables
- Legendre polynomials as 'Basis Functionals'
- Inputs are 1st order PCE's
- Use 4th Order PCEs for outputs
  - Compute coefficients using 5th order Gauss-Legendre Quadrature
- 2 dimensions, 5th order → 25 NESM runs

- Other methods: Monte Carlo, Latin Hypercube Sampling

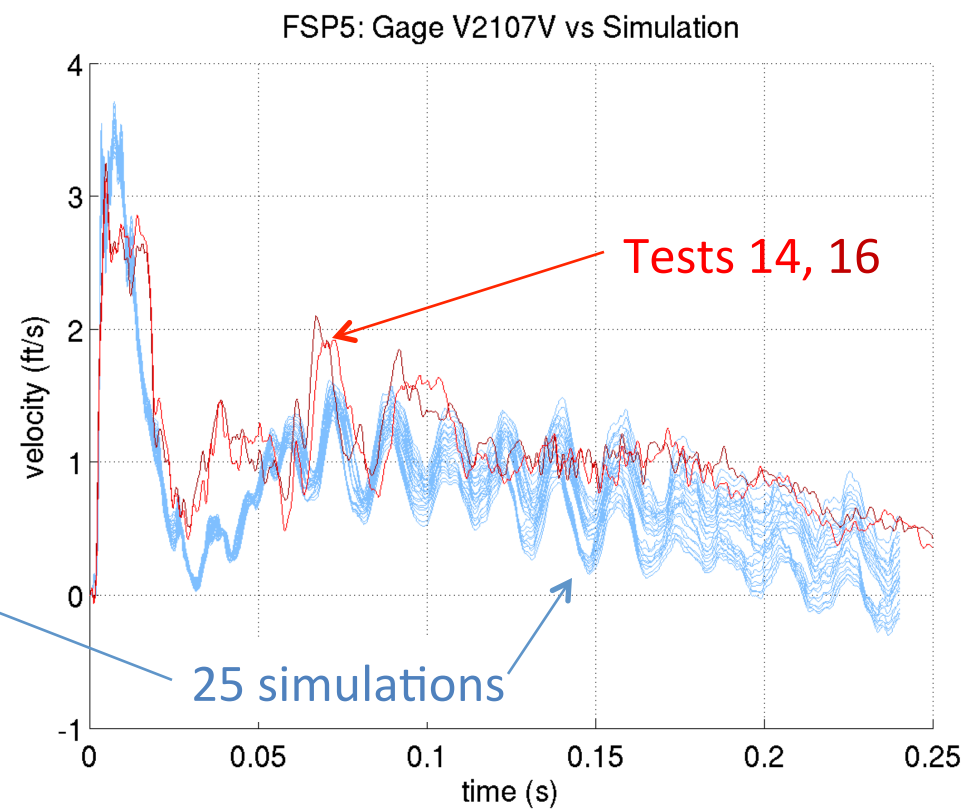
Sandia National Laboratories

Sim vs. Tests: UNDEX loading on FSP

Parametric Input Space



Measured/simulated responses



- UNDEX Charge mass → variation at early time
- Damping → variation at later times

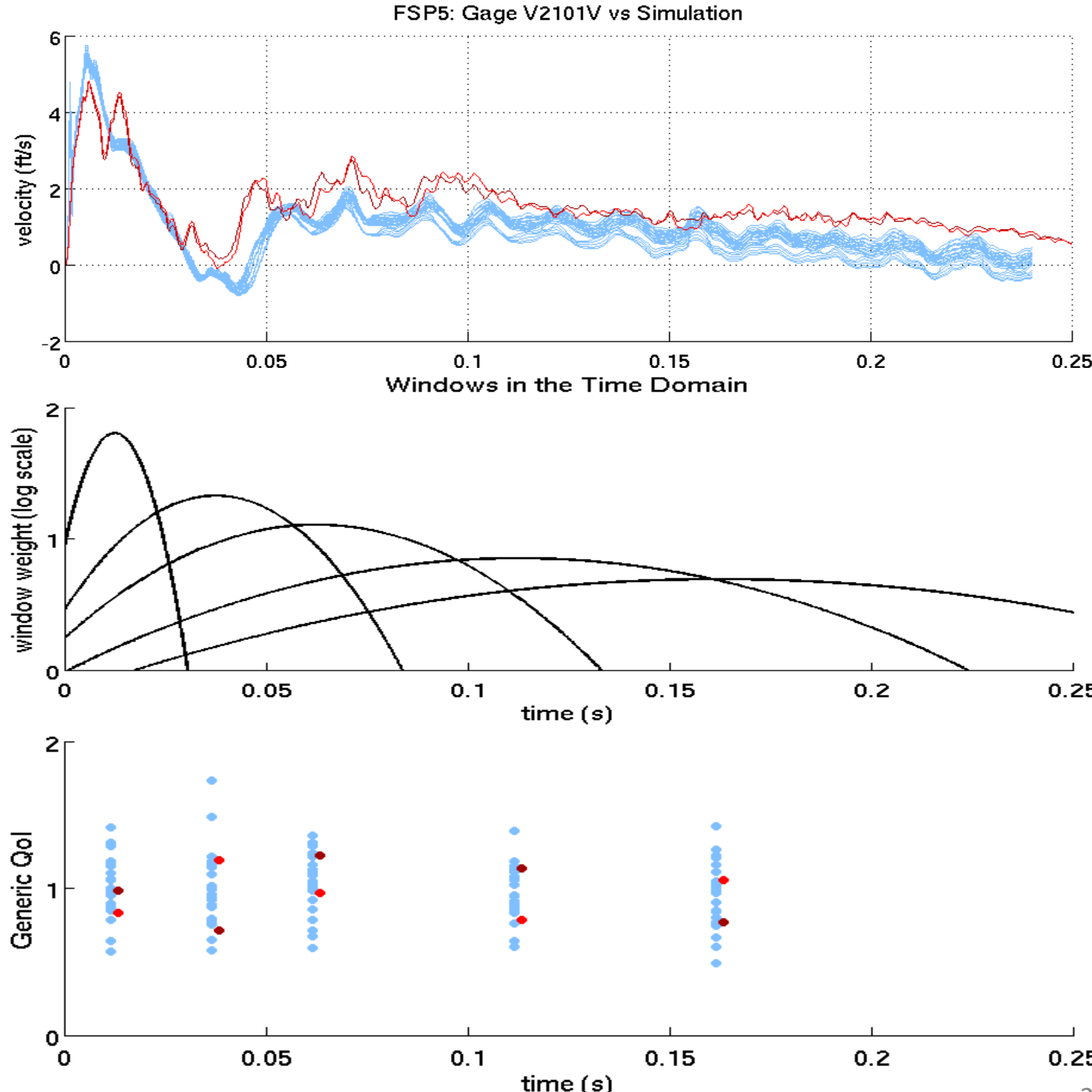
Sandia National Laboratories

QoIs = Windowed Measures

Start w/ signals for test and simulation

Integrate signal, weighted by window

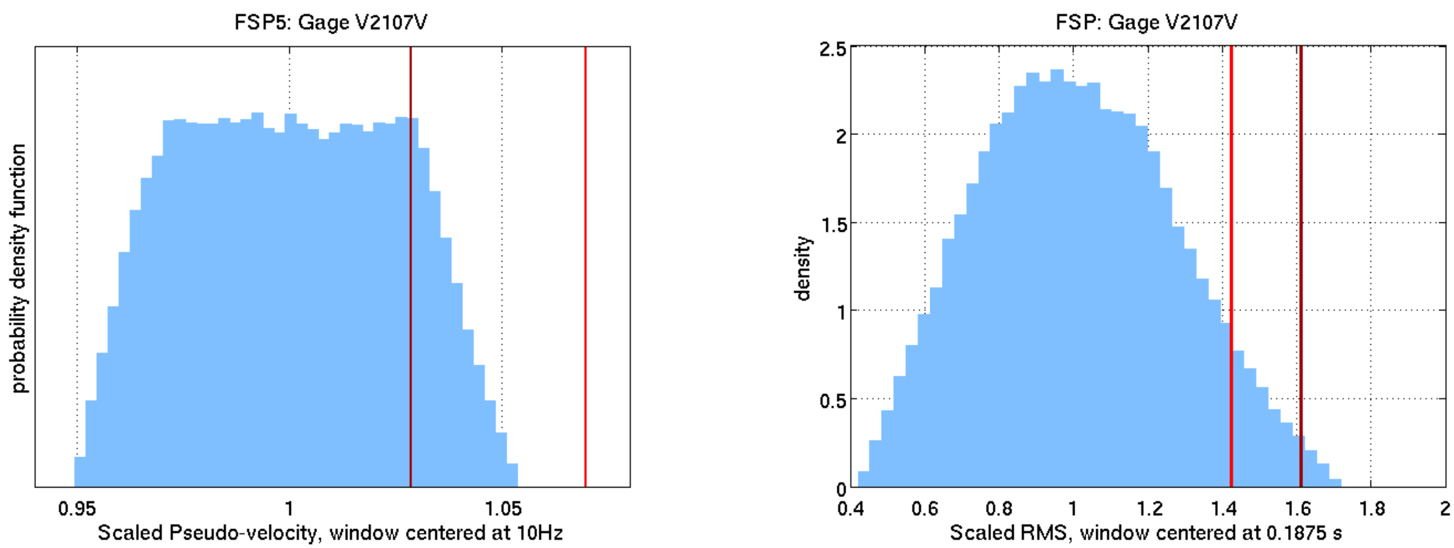
→ windowed measures, used as QoIs



Sandia National Laboratories

UQ on QoIs

- Compute Polynomial Chaos Expansion coefficients from samples → full probability density function of each QoI



- Test QoIs are shown in red
  - Only 1 or 2 tests at the same conditions
  - Hard to estimate uncertainty/error

Sandia National Laboratories

Validation Checklist

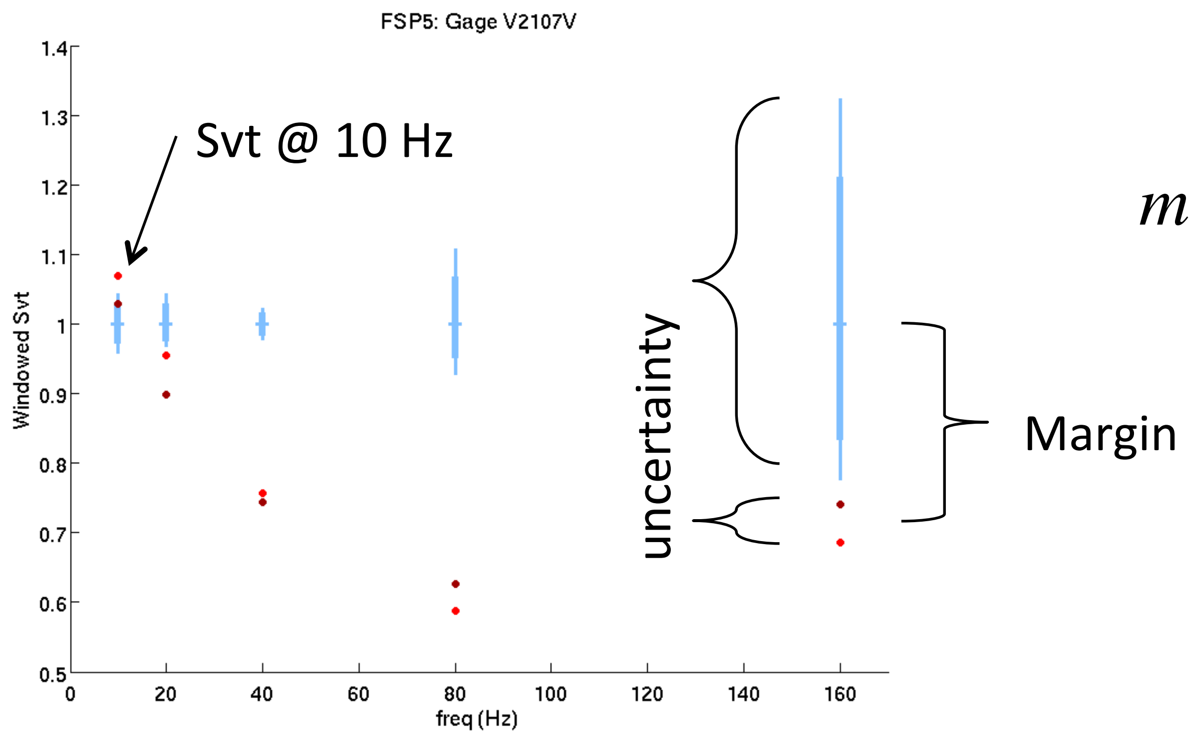
- Use hierarchy to make best use of data
- Define Quantities of Interest, derived from responses

- Identify and characterize sources of uncertainty
  - Both physical sources and modeling sources
- Propagate effect of uncertainty to simulation responses (UQ)

- **Compare Quantities of Interest from test and simulation (Validation)**

Sandia National Laboratories

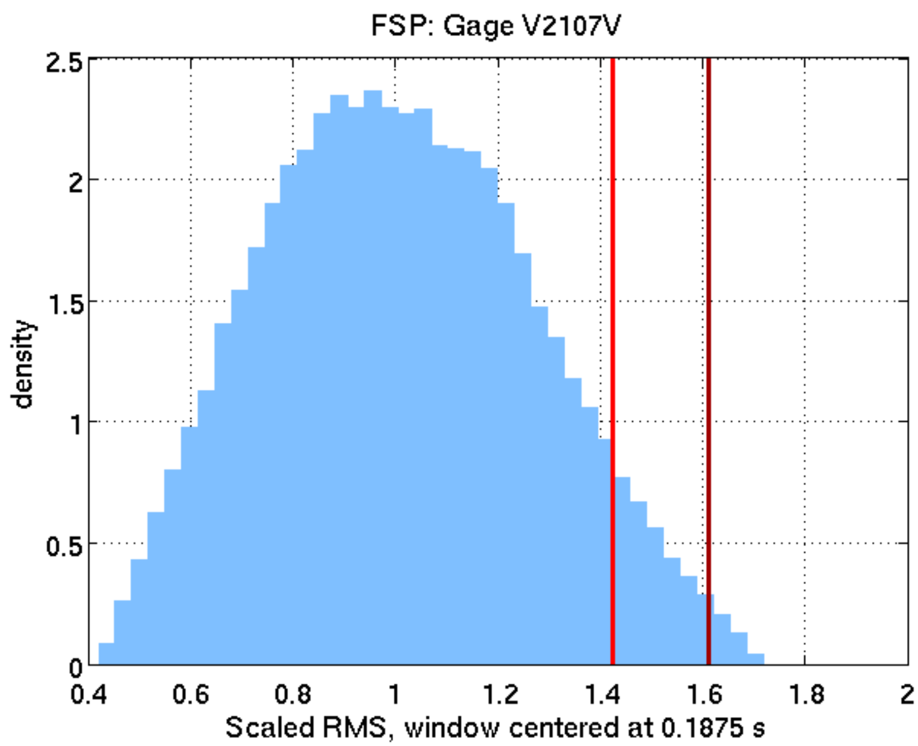
Validation Metrics 1: Quantitative Comparisons of QoIs



$$m2u = \frac{\text{margin}}{\text{uncertainty}}$$

Does the uncertainty in test and simulation explain discrepancy between test and simulation?

Validation Metrics 2: Hypothesis Testing Approach



- Do the test and simulations ‘match’?
- How probable is it that the test QoIs were drawn from the population of QoIs derived from the simulations?

Sandia National Laboratories

Summary

- FY12 – program demonstrated the validation process

- NSWC Carderock developed M&S capabilities for UNDEX / Airgun loading and structural responses
- Quantities of Interest → Isolate specific features
  - Windowed measures may be useful QoIs
- Validation Metrics compare QoIs from test & sim
- End goal – establish credibility in M&S predictions
  - Validation process must incorporate engineering judgment

Future Work

- Greater coverage of V&V hierarchy
- Investigation of uncertainty sources
- Independent calibration and validation
- More experience with windowed measures as QoIs
  - Have seen correlation between QoIs and features of velocity time histories

  → 'Credible' predictions of responses to UNDEX & Airgun
  - Do QoIs correlate with damage potential?

  → Make comparison of damage from UNDEX & Airgun

Sandia National Laboratories